Establishing Celestial Reference Frames At Different Ranges of Wavelengths

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JENAM-2011

July 4-8, 2011

Fundamental Catalogues (Stellar)

• FK3	A. Kopff, 1938	1535 stars
• FK4	W. Fricke, A. Kopff, 1963	1535 stars
• FK5	W. Fricke, 1988	1535 stars

(in accordance with a resolution of the XV IAU General Assembly in Sydney, 1973)

- Such catalogues are oriented with respect to the equator of the Earth projected on the sky and the vernal equinox related to the Earth's orbit.
- Mean precision of FK5 is 0.02” in position, 0.8 mas/yr in proper motion.

Resolution C1 of the XX IAU General Assembly, Baltimore, 1988
Section 3:

The IAU should adopt a celestial reference based upon a consistent set of coordinates for a sufficient number of suitable extragalactic objects when the required observational data have been successfully obtained and appropriately analyzed. This reference frame should be based upon a common, simultaneous discussion of the observations using agreed upon conventions. This reference frame is likely to be based, initially at least, exclusively upon radio astrometry, and transformations between this reference frame and the conventional celestial and terrestrial reference systems as well as the dynamical frame should be defined. The reference frame should be updated as required.

International Celestial Reference System (ICRS)

The ICRS is the idealized barycentric coordinate system to which celestial positions are referred. It is kinematically nonrotating with respect to the ensemble of distant extragalactic objects. It has no intrinsic orientation but was aligned close to the mean equator and dynamical equinox of J2000.0 for continuity with previous fundamental reference systems. Its orientation is independent of epoch, ecliptic or equator and is realized by a list of adopted coordinates of extragalactic sources.

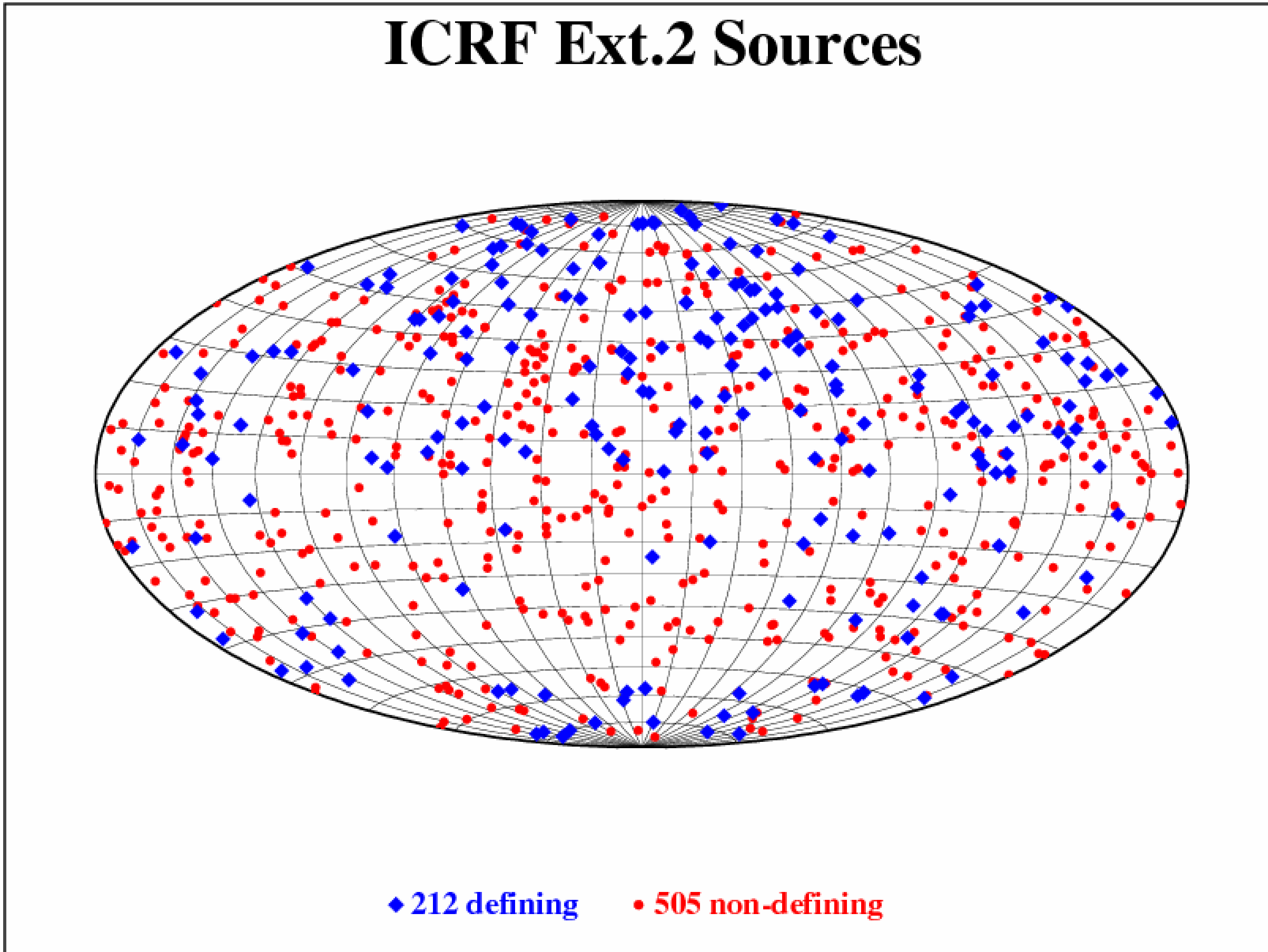
International Celestial Reference Frame (ICRF)

As adopted by the XXIII IAU General Assembly, Kyoto, 1997

The ICRF is a set of extragalactic objects whose adopted positions and uncertainties realize the ICRS axes and give the uncertainties of the axes. It is also the name of the radio catalogue whose 212 defining sources are currently the most accurate realization of the ICRS. Note that the orientation of the ICRF catalogue was carried over from earlier IERS radio catalogues and was within the errors of the standard stellar and dynamical frames at the time of adoption. Successive revisions of the ICRF are intended to minimize rotation from its original orientation. Other realizations of the ICRS have specific names (e.g., the Hipparcos Celestial Reference Frame).

ICRF

- S/X data and analysis through 1995
- ICRF-Ext.1, ICRF-Ext.2
- 212 defining sources
- Position uncertainty ≥ 250 μas
- Accuracy of axes ~30 μas
- Orientation independent of equator, ecliptic and equinox


ICRF Ext.2 Sources
212 defining
505 non-defining

The Second Realization of the International Celestial Reference Frame

IERS/IVS Working Group

Charter: The purpose of the working group is to generate the second realization of the ICRF from VLBI observations of extragalactic radio sources, consistent with the current realization of the ITRF and EOP data products. The working group will apply state-of-the-art astronomical and geophysical models in the analysis of the entire relevant S/X astrometric and geodetic VLBI data set. The working group will carefully consider the selection of defining sources and the mitigation of source position variations to improve the stability of the ICRF. The goal is to present the second ICRF to relevant authoritative bodies, e.g. IERS and IVS, and submit the revised ICRF to the IAU Division I working group on the second realization of the ICRF for adoption at the 2009 IAU general assembly.

Goal: Produce ICRF2 for IERS/IVS consideration and for submission to the IAU Working Group.

Active: 2006-2010

Members:

O. Titov, Australia	G. Engelhardt, Germany	V. Zharov, Russia
R. Heinkelmann, Austria	A. Nothnagel, Germany	S. Bolotin, Ukraine
G. Wang, China	V. Tesmer, Germany	D. Boboltz, USA
F. Arias, France	G. Bianco, Italy	A. Fey, USA
P. Charlot, France	S. Kurdubov, Russia	R. Gaume, USA
A.-M. Gontier, France	Z. Malkin, Russia	C. Jacobs, USA
S. Lambert, France	E. Skurikhina, Russia	C. Ma, USA (Chair)
J. Souchay, France	J. Sokolova, Russia	L. Petrov, USA
		O. Sovers, USA

ICRF2 Highlights

3414 Compact Extragalactic sources

5 times more than ICRF1

Noise floor of approximately 40 micro-arcsec

5-6 times better than ICRF1

Axis stability of approximately 10 micro-arcsec

2 times better than ICRF1

IERS Technical Note 35: The Second Realization of the International Celestial Reference Frame by Very Long Baseline Interferometry, Presented on behalf of the IERS / IVS Working Group, A. Fey, D. Gordon and C. Jacobs (eds.). (IERS Technical Note 35) Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie, 2009. 204 p.

http://www.iers.org/nn_11216/IERS/EN/Publications/TechnicalNotes/tn35.html

ICRF2 Solution

Generated using CALC/SOLVE at GSFC

- single solution as opposed to combination
- preserves consistency between CRF / EOP / TRF

4540 VLBI sessions - 1979 August 3 and 2009 March 16

6.5 million observations (group delay only)

3375 “global” source positions

39 “arc” source positions (special handling sources)

Formal errors inflated

- scaled by a factor of 1.5 (same as ICRF1)
- root-sum-square with 0.040 mas (a factor of 6 smaller than ICRF1)

Selection of ICRF2 Defining Sources

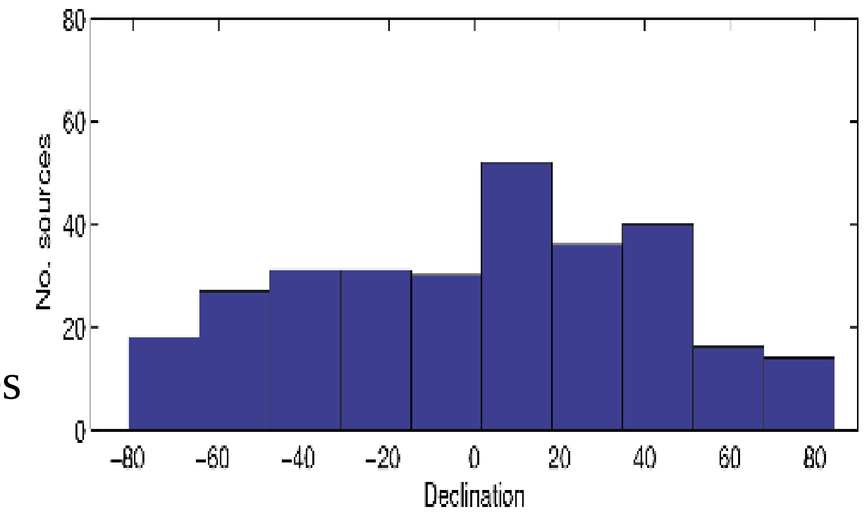
Criteria for consideration

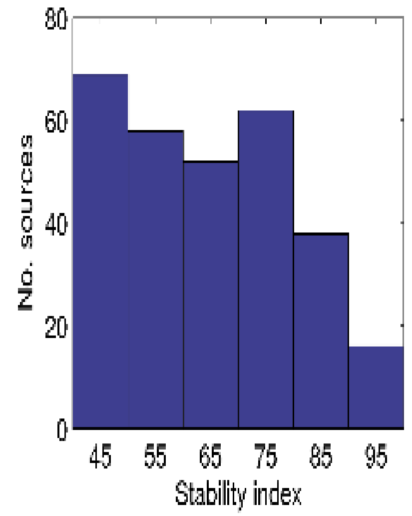
- Position estimated "globally"
- Observed in at least 10 sessions
- Greater than 2-year observation history

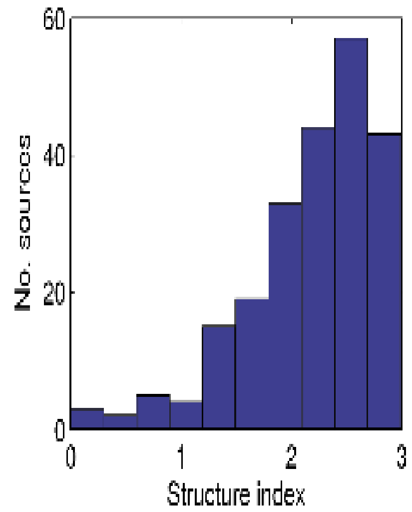
Sources ranked based on

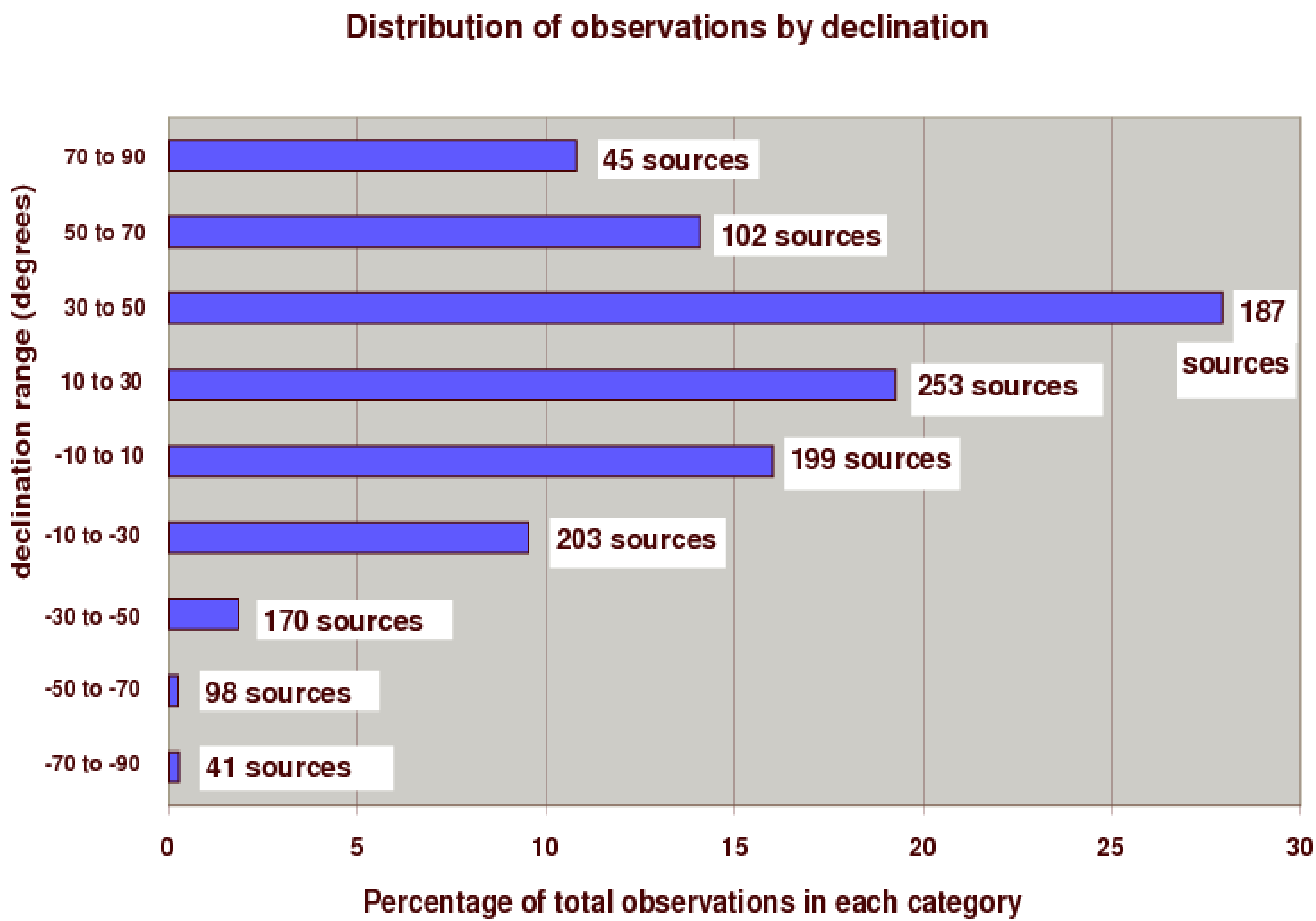
- Position stability from position time series
- Formal error from least-squares solution
- Structure Index

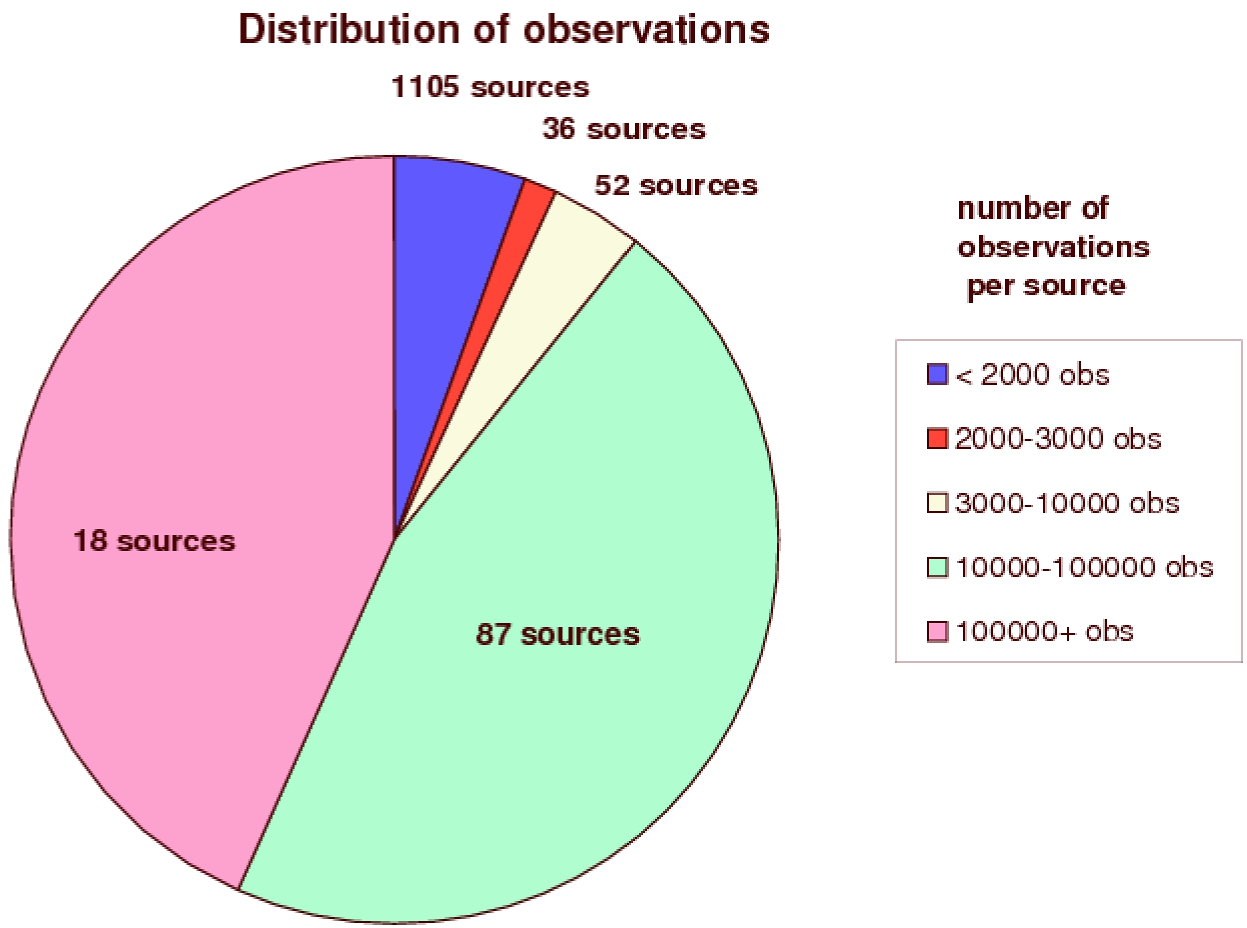
Selection made on basis of axis stability as a function of the number of "defining" sources (see TN35 for explanation)



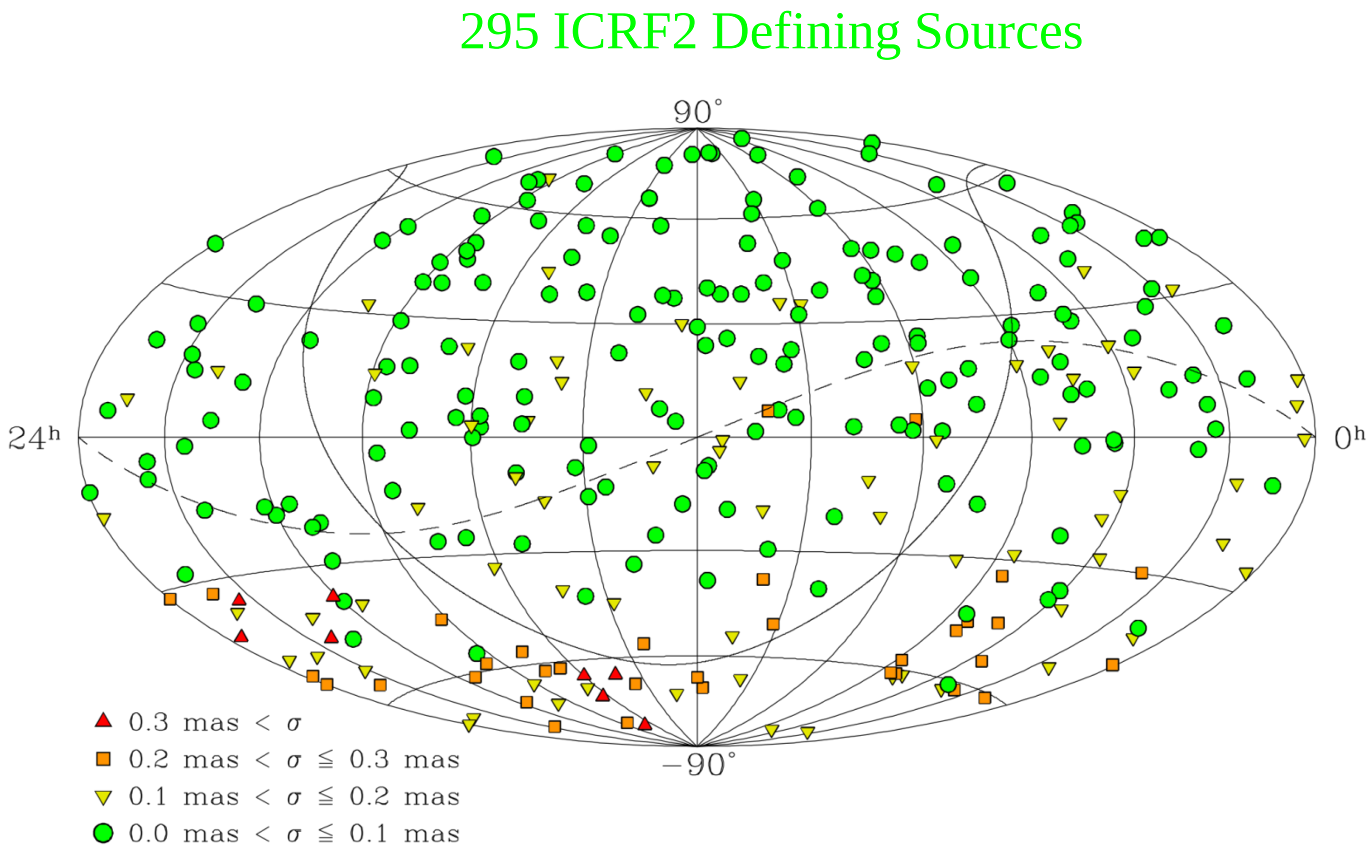




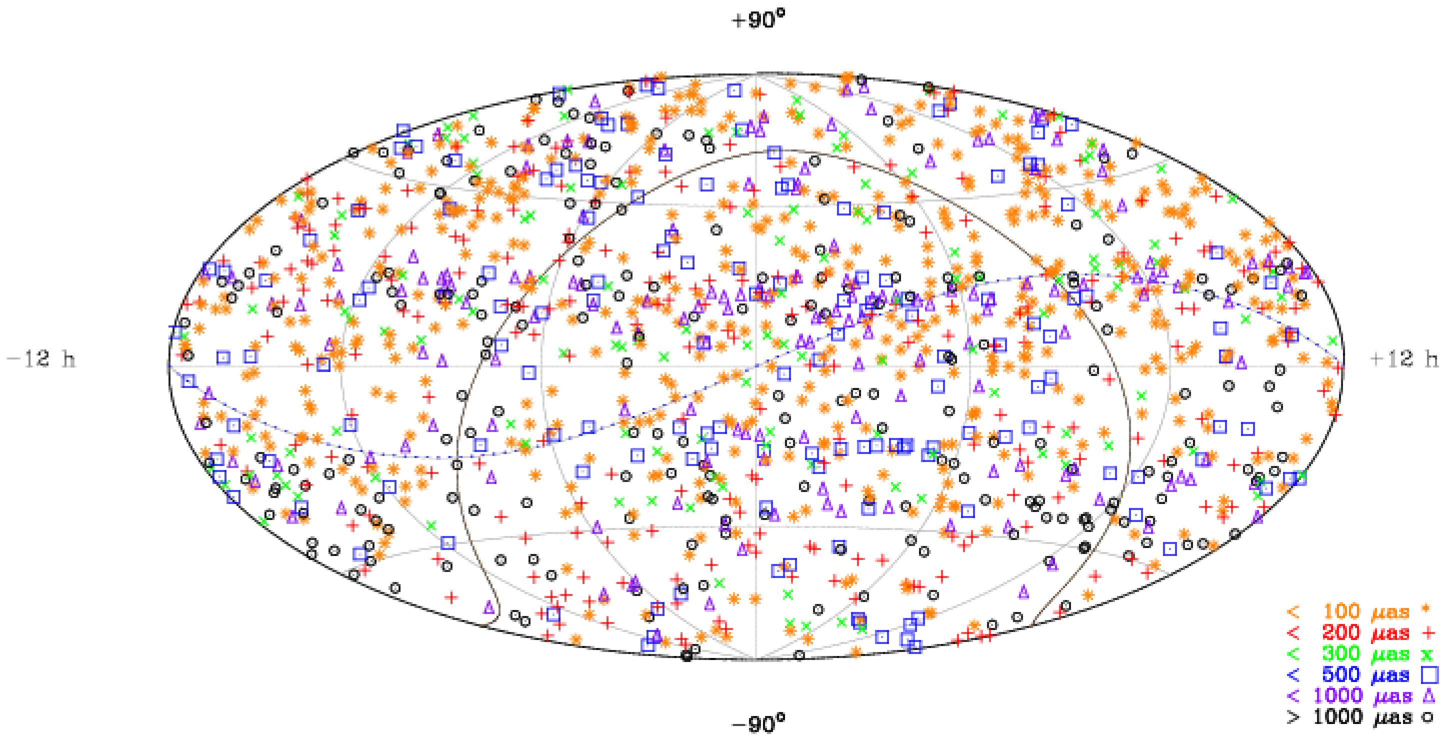

Distribution of observations by declination
declination range (degrees)
70 to 90
50 to 70
30 to 50
10 to 30
-10 to 10
-10 to -30
-30 to -50
-50 to -70
-70 to -90
45 sources
102 sources
187 sources
253 sources
199 sources
203 sources
170 sources
98 sources
41 sources
0
5
10
15
20
25
30
Percentage of total observations in each category


Distribution of observations
1105 sources
36 sources
52 sources
18 sources
87 sources
number of observations per source
< 2000 obs
2000-3000 obs
3000-10000 obs
10000-100000 obs
100000+ obs

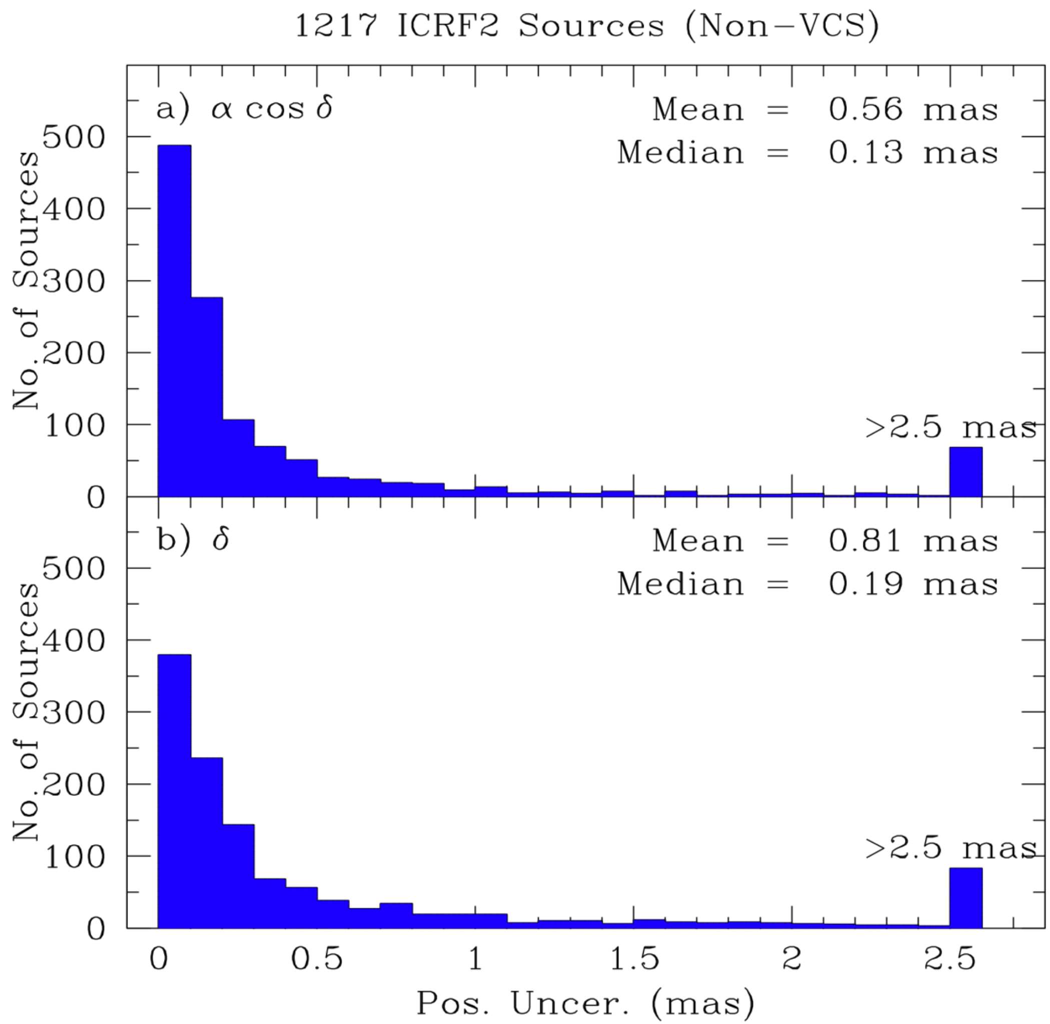
The Second Realization of the International Celestial Reference Frame



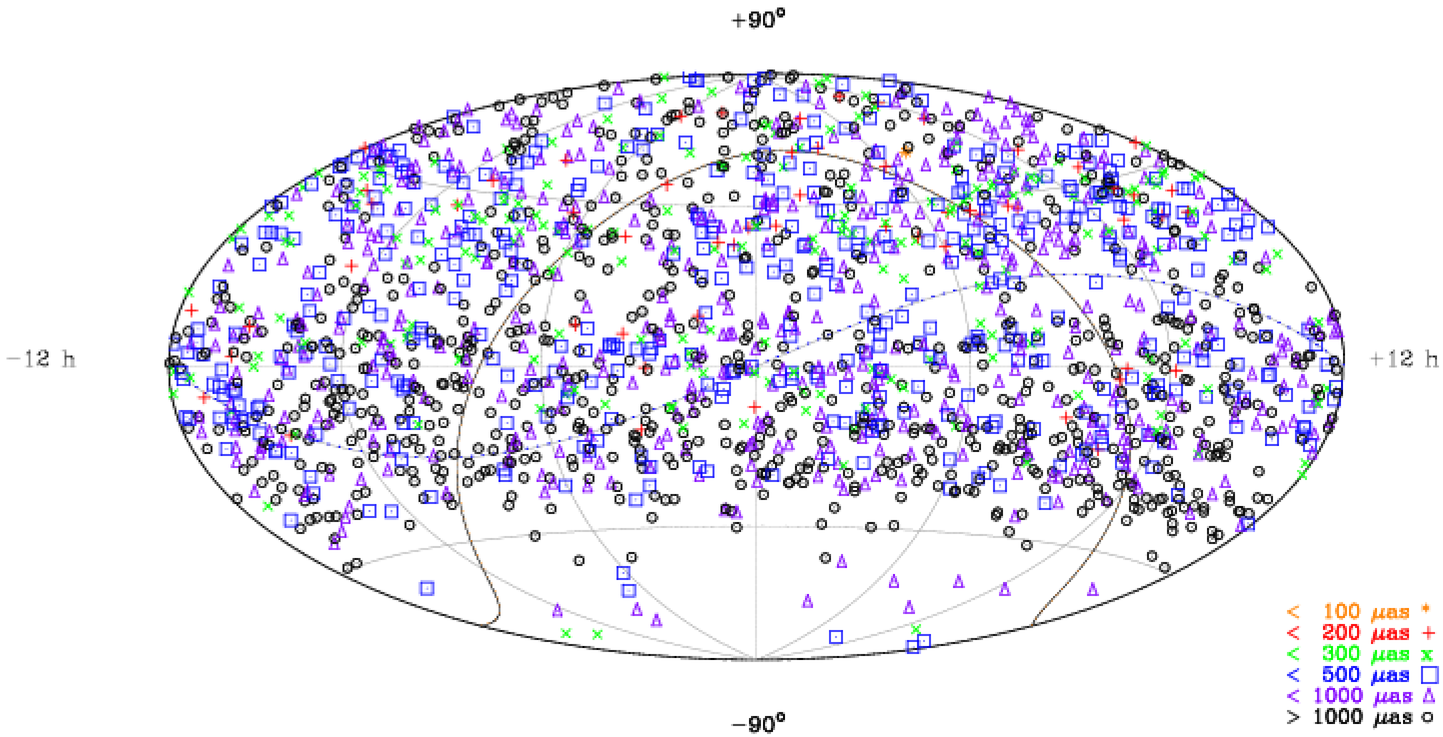
1448 ICRF2 Sources observed in multiple sessions



Plotted are formal errors as indicated by the key


1217 ICRF2 Sources (Non−VCS)
a) α cos δ
Mean = 0.56 mas
Median = 0.13 mas
>2.5 mas
b) δ
Mean = 0.81 mas
Median = 0.19 mas
>2.5 mas
No. of Sources
Pos. Uncer. (mas)
0
100
200
300
400
500
0
0.5
1
1.5
2
2.5

1966 ICRF2 Sources observed in single sessions



Plotted are formal errors as indicated by the key

These are mostly VLBA Calibrator Survey (VCS) sources

RESOLUTION B3
on
the Second Realization of the
International Celestial Reference Frame

The International Astronomical Union XXVII General Assembly,

noting

1. that Resolution B2 of the XXIII General Assembly (1997) resolved "That, as from 1 January 1998, the IAU celestial reference system shall be the International Celestial Reference System (ICRS)",
2. that Resolution B2 of the XXIII General Assembly (1997) resolved that the "fundamental reference frame shall be the International Celestial Reference Frame (ICRF) constructed by the IAU Working Group on Reference Frames",
3. that Resolution B2 of the XXIII General Assembly (1997) resolved "That IERS should take appropriate measures, in conjunction with the IAU Working Group on reference frames, to maintain the ICRF and its ties to the reference frames at other wavelengths",
4. that Resolution B7 of the XXIII General Assembly (1997) recommended "that high-precision astronomical observing programs be organized in such a way that astronomical reference systems can be maintained at the highest possible accuracy for both northern and southern hemispheres",
5. that Resolution B1.1 of the XXIV General Assembly (2000) recognized "the importance of continuing operational observations made with Very Long Baseline Interferometry (VLBI) to maintain the ICRF",

RESOLUTION B3
on
the Second Realization of the
International Celestial Reference Frame

recognizing

1. that since the establishment of the ICRF, continued VLBI observations of ICRF sources have more than tripled the number of source observations,
2. that since the establishment of the ICRF, continued VLBI observations of extragalactic sources have significantly increased the number of sources whose positions are known with a high degree of accuracy,
3. that since the establishment of the ICRF, improved instrumentation, observation strategies, and application of state-of-the-art astrophysical and geophysical models have significantly improved both the data quality and analysis of the entire relevant astrometric and geodetic VLBI data set.,
4. that a working group on the ICRF formed by the International Earth Rotation and Reference Systems Service (IERS) and the International VLBI Service for Geodesy and Astrometry (IVS), in conjunction with the IAU Division I Working Group on the Second Realization of the International Celestial Reference Frame has finalized a prospective second realization of the ICRF in a coordinate frame aligned to that of the ICRF to within the tolerance of the errors in the latter (see note 1),
5. that the prospective second realization of the ICRF as presented by the IAU Working Group on the Second Realization of the International Celestial Reference Frame represents a significant improvement in terms of source selection, coordinate accuracy, and total number of sources, and thus represents a significant improvement in the fundamental reference frame realization of the ICRS beyond the ICRF adopted by the XXIII General Assembly (1997),

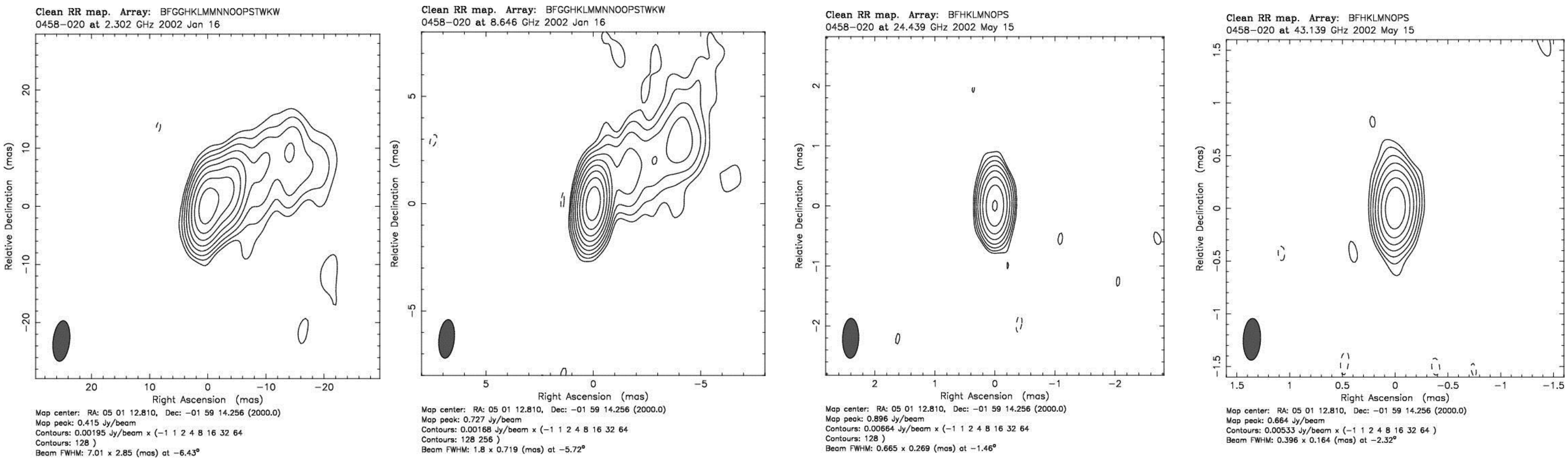
RESOLUTION B3
on
the Second Realization of the
International Celestial Reference Frame

resolves

1. that from 01 January 2010 the fundamental astrometric realization of the International Celestial Reference System (ICRS) shall be the Second Realization of the International Celestial Reference Frame (ICRF2) as constructed by the IERS/IVS working group on the ICRF in conjunction with the IAU Division I Working Group on the Second Realization of the International Celestial Reference Frame (see note 1),
2. that the organizations responsible for astrometric and geodetic VLBI observing programs (e.g. IERS, IVS) take appropriate measures to continue existing and develop improved VLBI observing and analysis programs to both maintain and improve ICRF2,
3. that the IERS, together with other relevant organizations continue efforts to improve and densify high accuracy reference frames defined at other wavelengths and continue to improve ties between these reference frames and ICRF2.

Note 1: The Second Realization of the International Celestial Reference Frame by Very Long Baseline Interferometry, Presented on behalf of the IERS / IVS Working Group, Alan Fey and David Gordon (eds.). (IERS Technical Note ; 35) Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie, 2009. See <www.iers.org/MainDisp.csl?pid=46-25772> or <hpiers.obspm.fr/icrs-pc/> .

Source Structure vs. Wavelength



S-band
2.3 GHz
13.6cm

X-band
8.6 GHz
3.6cm

K-band
24 GHz
1.2cm

Q-band
43 GHz
0.7cm

Ka-band
32 GHz
0.9cm

The sources become better ----->

Image credit: P. Charlot et al, AJ, 139, 5, 2010

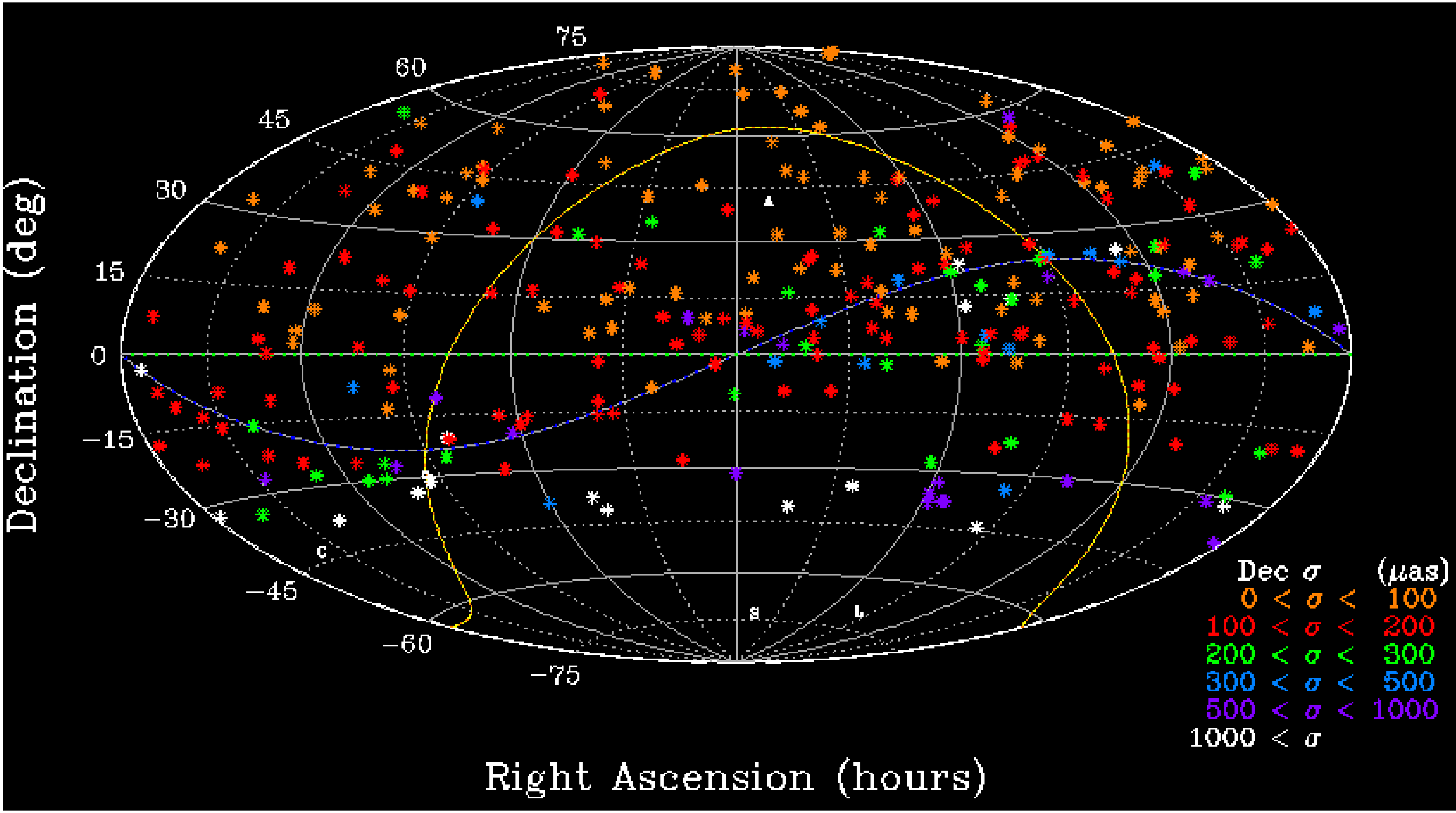
Status of current radio-based celestial frames

- ICRF2: wavelength 3.6cm, 3.4K objects, 40-100 μas
- K-band: wavelength 1.2cm, 0.3K objects, 100-250 μas
- X/Ka: wavelength 9mm, 0.5K objects, 200-300 μas
- Q-band: wavelength 7mm, 0.1K objects, 300-500 μas

- K/Q Collaboration (1.2cm,7mm or 24, 43 GHz)
  G.E. Lanyi, P.I.
  D.A. Boboltz, P. Charlot, A.L. Fey, E. B. Fomalont, B.J. Geldzahler,
  D. Gordon, C.S. Jacobs, C. Ma, C.J. Naudet, J.D. Romney, O.J. Sovers,
  L.D. Zhang

- X/Ka Collaboration (9mm, 32 GHz)
  C.S. Jacobs, P.I.
  J. Clark, C. Garcia-Miro, S. Horiuchi, I. Sotuela, O.J. Sovers

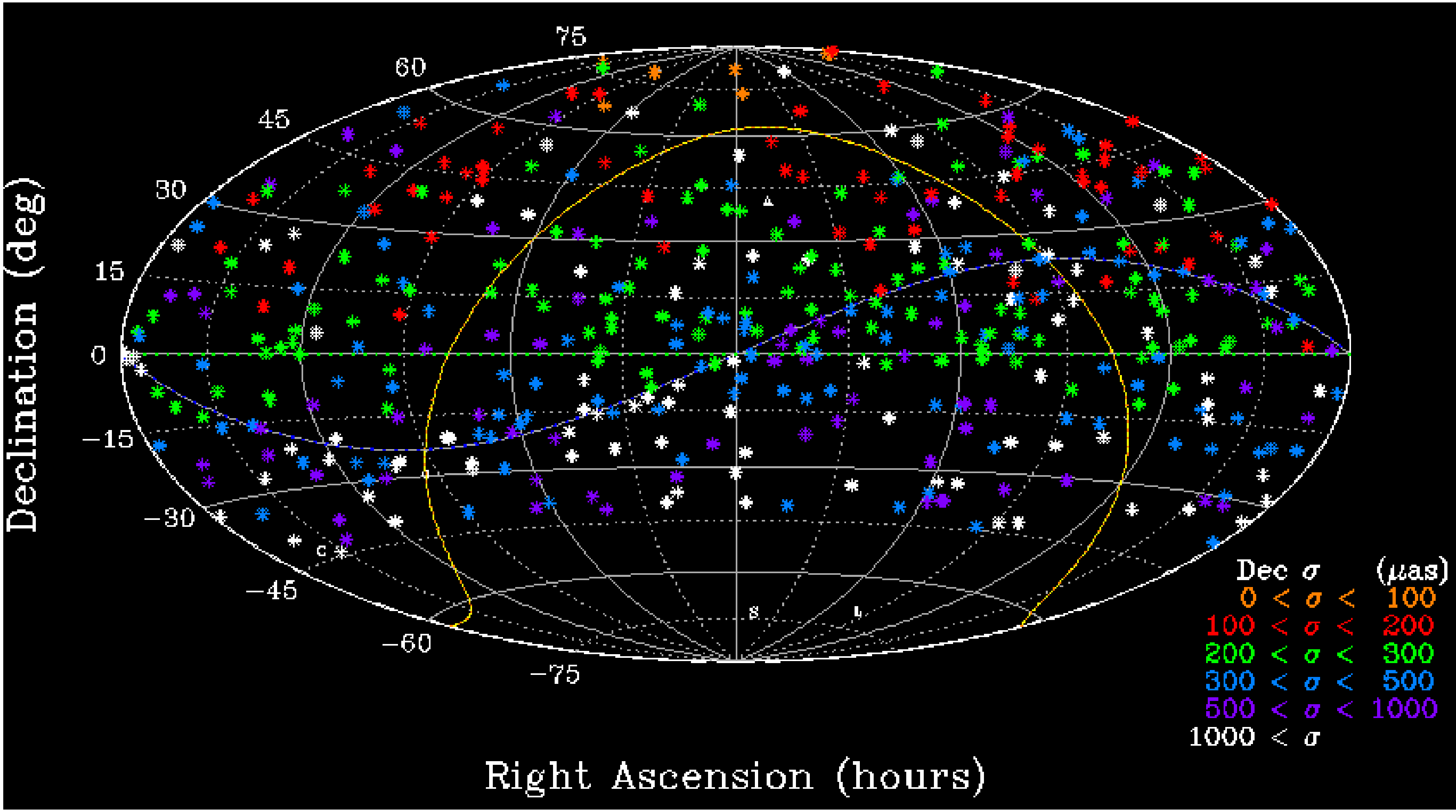
K-band 1.2cm: 278 Sources



VLBA all northern, poor below Dec. -30˚. ΔDec vs. Dec tilt= 500 μas

Credit: Lanyi et al, AJ, 139, 5, 2010; Charlot et al, AJ, 139, 5, 2010

X/Ka current results: 455 Sources

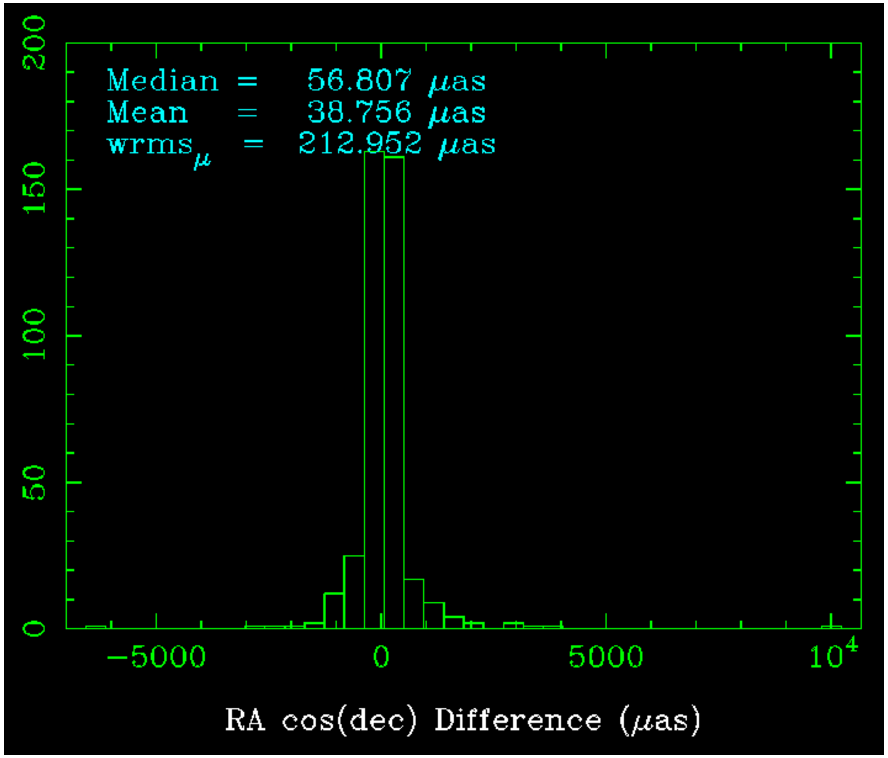


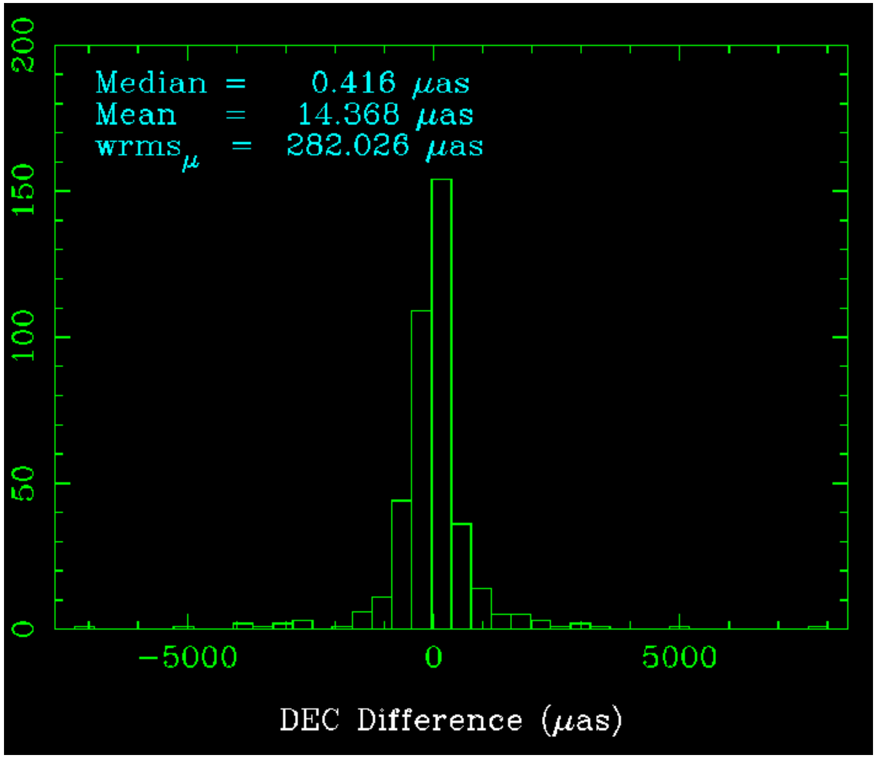
Cal. to Madrid, Cal. to Australia. Weakens southward. No ΔDec tilt

Credit: Jacobs et al, EVGA, Bonn, Germany, 2011

9mm (X/Ka) *vs.* ICRF2 at 3.6cm (S/X)

Accuracy of 404 X/Ka sources vs. S/X ICRF2 (current IAU standard)





RA: 213 μas = 1.0 nrad **Dec: 282 μas = 1.4 nrad**

Credit: X/Ka: Jacobs et al, EVGA, Bonn, Germany, 2011
S/X ICRF2: Ma et al, editors: Fey, Gordon & Jacobs, 2009

Improving VLBI

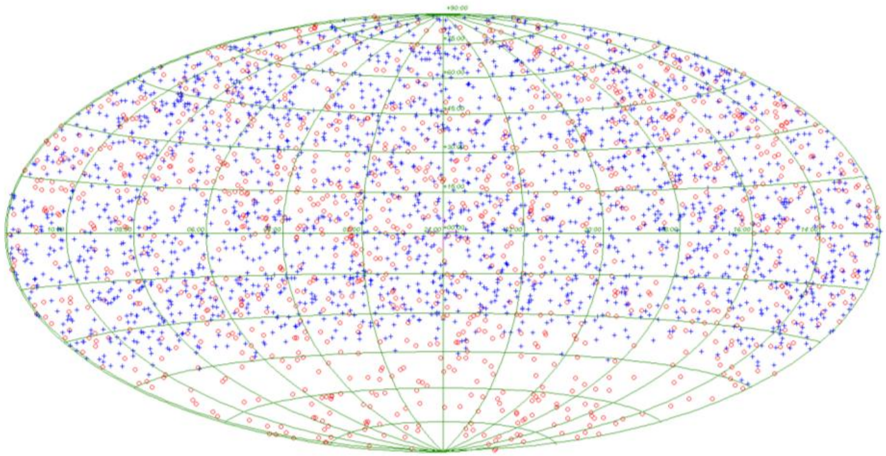
Systems analysis shows dominant errors are:

- Limited SNR/sensitivity
  - already increasing bit rates: 128 to 512 Mbps. Soon to 1Gbps?
  - 2 Gbps and 4 Gbps on the way.
- Instrumentation: already building better hardware
  - Digital Back Ends (filters), VLBI-2010
- Troposphere: better calibrations being explored for turbulent variations in signal delay
- **Weak geometry in Southern hemisphere**
  - Limits accuracy to about 200 µas level in declination
  - Few observations below declination of -45 Deg!
  - Few southern sites: Canberra & Hobart Australia, Hart, S. Africa

  - Need more sites in the Southern hemisphere

By 2020: Two extragalactic celestial reference frames available

VLBI (Radio)



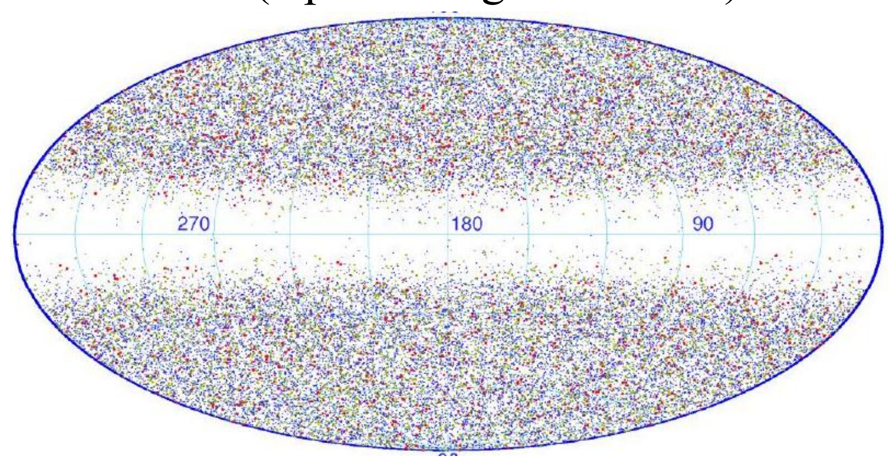
Position accuracy:

1997: ICRF1 − 717 sources − σ ≥ 250 μas

2009: ICRF2 − 3414 sources − σ ≥ 60 μas

2020: ICRF3 ???

Gaia (Optical magnitude ≤ 20)



Anticipated position accuracy:

20 000 QSOs @ V≤18 → 16 μas ≤ σ ≤ 70 μas

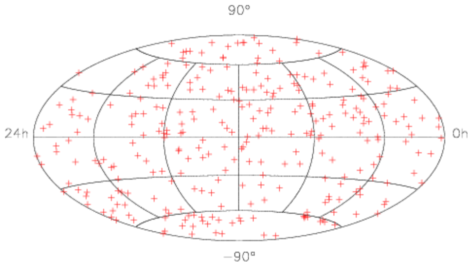
500 000 QSOs @ V≤20 → 16 μas ≤ σ ≤ 200 μas

Lindegren et al. 2008

Linking these 2 frames is important:

- to ensure continuity of the fundamental celestial reference frame
- to register optical & radio positions with the highest accuracy

Gaia-VLBI frames alignment



- **Requirements:**

✓ Several hundreds of common sources

✓ With a uniform sky coverage

✓ Common sources must have:

Accurate Gaia position → Optically-bright (mag. ≤ 18; *Mignard 2003*)

Accurate VLBI position → Good astrometric quality (point-like VLBI structure)

- **Current status:**

✓ ICRF1: 10% of sources suitable = 70 sources (*Bourda et al. 2008*)

✓ ICRF2: 6% of sources suitable = 201 sources

➡ Need to find new radio sources suitable for accurate Gaia–VLBI alignment

Program Plan

- Idea: New candidates → Weak sources (< 100 mJy)

- Specific VLBI observing program designed (with EVN & VLBA)

- Observing Sample: 447 weak extragalactic radio sources

✓ NVSS catalog (excluding ICRF1 and VCS sources)
✓ Optical magnitude $V \leq 18$
✓ Total flux density (NVSS) ≥ 20 mJy
✓ $\delta \geq -10^{\circ}$

NRAO VLA Sky Survey
(Condon et al. 1998)

- Observing Strategy:

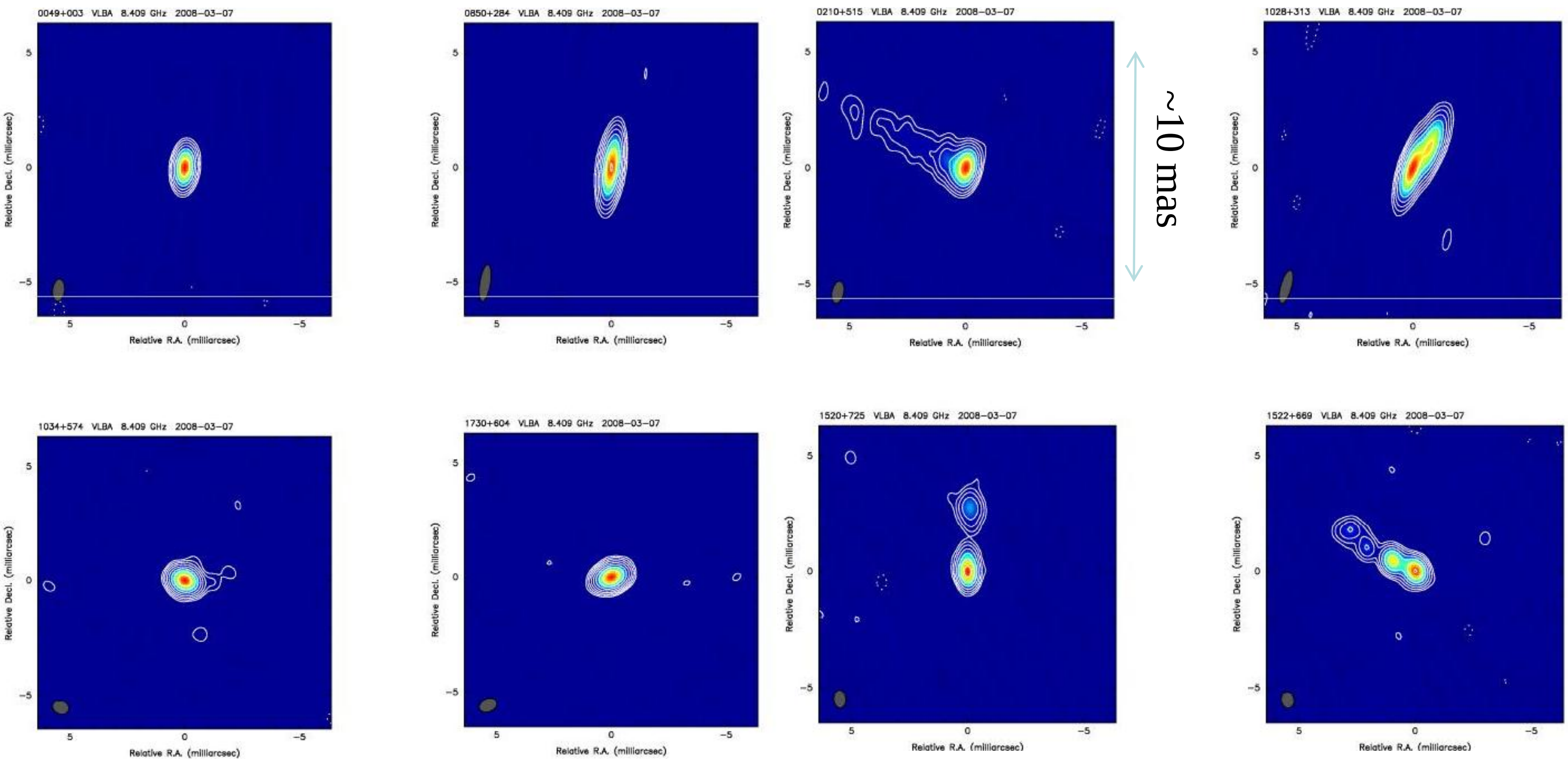
1. VLBI detection (*Bourda et al. 2010, A&A 520, A113*)
2. Imaging (*Bourda et al. 2011, A&A 526, A102*)
3. Accurate astrometry (for the most compact sources)

Program Team: G. Bourda, A. Collioud, P. Charlot, R. Porcas, S. Garrington

Pilot imaging experiment: Examples of VLBI maps

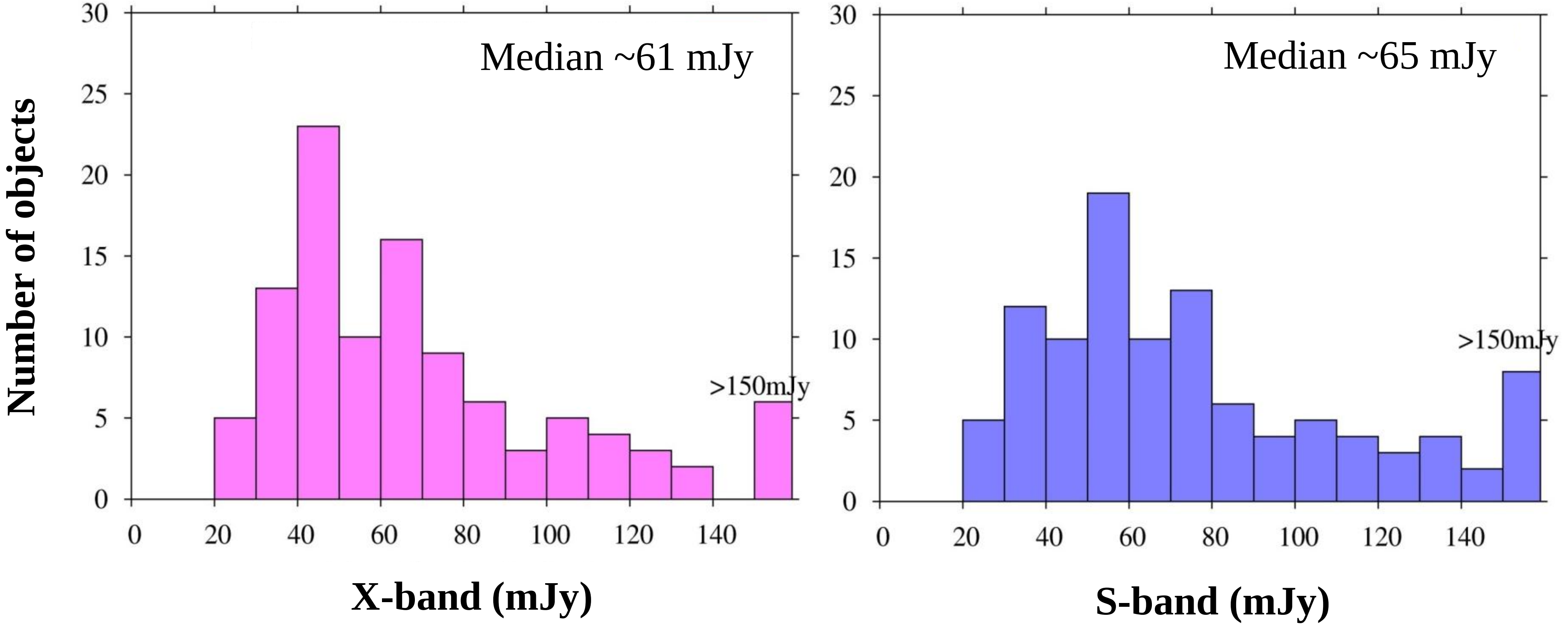
"Good" sources

"Bad" sources



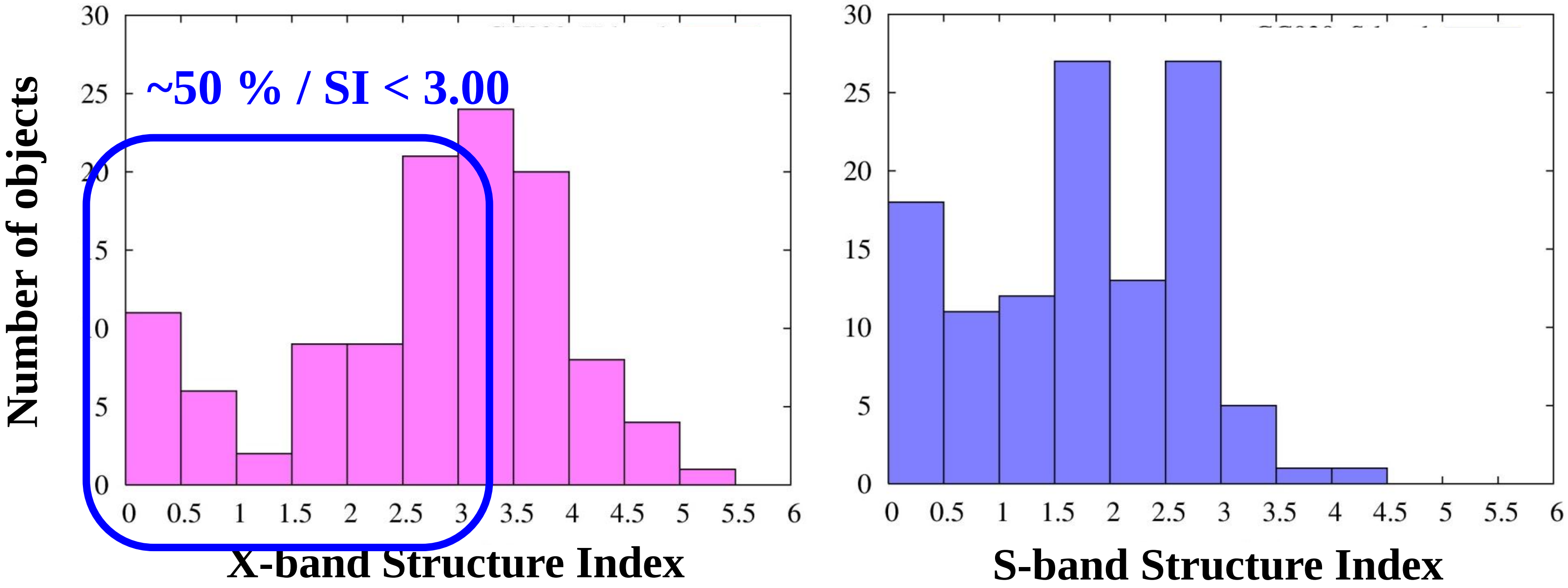
X-band −1st contour level @ 1%

Pilot imaging experiment: Total flux density distribution



Pilot imaging experiment: Structure Index
Astrometric quality

- Same criterion as for the selection of ICRF2 "defining" sources (continuous structure index < 3.0)



→ ~50% of sources point-like or with compact structures (i.e. 47 sources)

Summary and Future prospects

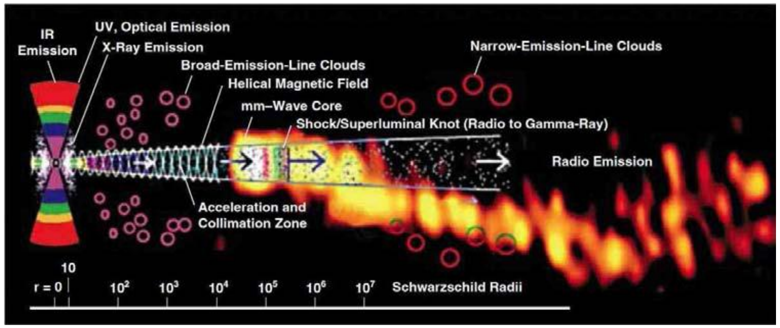
<u>Step 1</u>
VLBI
detection
☑

<u>Step 2</u>
VLBI
imaging
☑…

<u>Step 3</u>
VLBI
Astrometry
☐

- To finish this program:

✓ Carry out global astrometry (on the most compact sources)
✓ Positions wanted to better than <100 μas
✓ First proposal during the year 2011



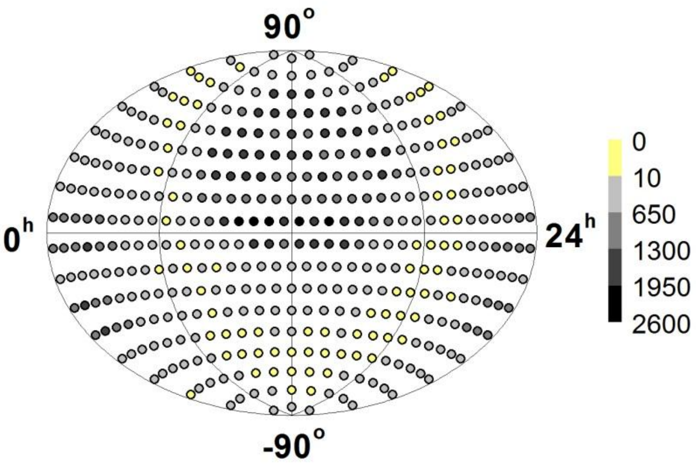
- In the "near" future:

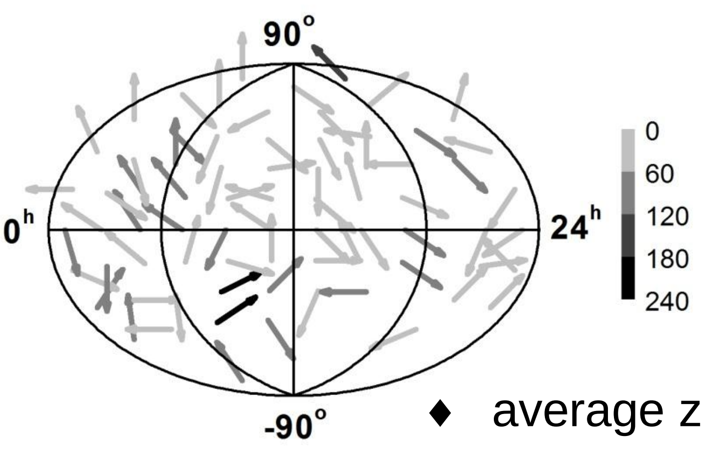
✓ Cover southern hemisphere
✓ Astrophysics: Issues of core shifts
✓ Ultimately the Gaia *link* sources could/should be part of the ICRF3 to be constructed by 2020

Gaia Initial QSO Catalog – GIQC IV

- **187,505 objects**: DEFINING, CANDIDATES, OTHER.
- DEFINING= 136,643 well documented QSOs – 103,422 from SDSS/DR8
- CANDIDATES= 24,227 objects - 1,075 from ICRF2
  - 15,373 optically pointlike AGNs
  - 7,779 poor record QSOs
- OTHER= 26,635 objects - 385 radio-quasars
  - 23,178 faint objects
  - 2,985 unreliable detections
  - 87 empty fields

- Reliable redshift for 183,543 objects (97.87% of the catalog)
- Reliable optical mages for 159,701 objects (85.17% of the catalog)



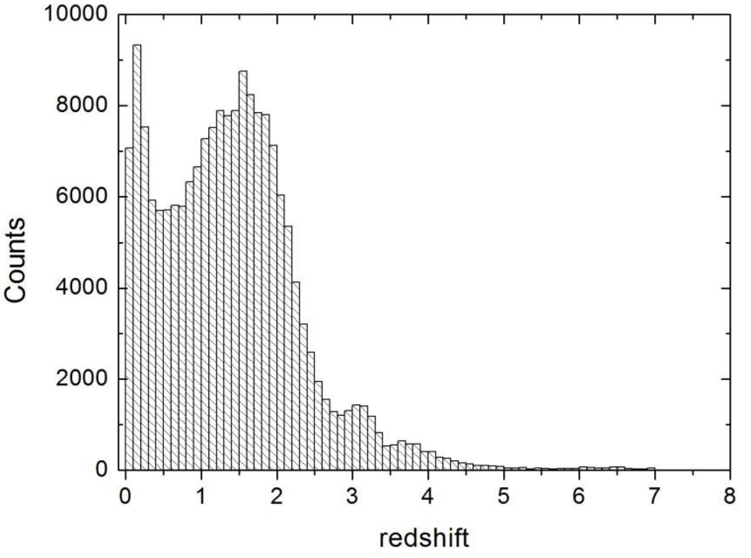


- average zonal errors of 50mas
- average precision at 150mas.

Morphology and the signature of the host galaxy

♥ The largest fraction of GAIA QSOs would be of nearby ones.

♥ Average z = 1.18



♥ One might expect a fair amount of contamination by alien AGNs among the GAIA extragalactic reference frame

(because they would look alike by the GAIA QSO selection criteria,

and because they still would look point-like).

♥ One might expect a fair amount of resolved host galaxies around the GAIA extragalactic reference frame QSOs

(because the host galaxies do are large and bright enough,

because of contamination by alien AGNs,

and because the QSOs will be nearby ones).

Astrometric and photometric variability

♣ Quasars vary intrinsically on timescales of months to years. Several physical processes are discussed as important causes of this variability: foremost are accretion disc instabilities, but also large-scale changes in the amount of in-falling material may be important, starbursts in the host galaxy, micro lensing by the host galaxy and compact dark matter objects, and stochasticity of multiple supernovae. Irrespective of the physics behind the variability, quasars are observed to exhibit brightness variations, of typically >10% over several years (Schmidt et al., 2010).

♣ How stable will a reference frame be? It is well known that variable intrinsic structure of AGN at radio wavelengths has a significant impact on (degrades) radio positional accuracy. Currently, there is very little available information on whether the optical counterparts of the radio objects are compact at the sub-mas astrometric precision. Although the core of a quasar's optical emission may originate in a region as small as 1 pc (200 μas at 1 Gpc), some degree of photo-center wander should be expected, probably correlated with optical variability. Motion of a quasar's photo-center may also result from a variable nucleus in combination with effects in the larger (albeit fainter) host galaxy (Johnston et al., 2004).

GAIA Initial QSO Catalogue

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Sonia Anton (Centro de Investigação em Ciências Geo-Espaciais/FCUP and SIM)
Christophe Barache (SYRTE/Observatoire de Paris)
Sébastien Bouquillon (SYRTE/Observatoire de Paris)
Geraldine Bourda (Observatoire de Bordeaux)
Jean-François Le Campion (Observatoire de Bordeaux)
Patrick Charlot (Observatoire de Bordeaux)
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Summary and final thoughts

More sources, flux and data at lower radio frequencies

More compact, less core shift at higher frequencies

Direct ground access to the CRF will stay with radio

The optical CRF data from Gaia will be from one time